Ion Beam Heated Target Simulations and Analysis For Warm Dense Matter Physics and Inertial Fusion Energy*

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1. LLNL 2. LBNL 3. PPPL 4.Tech-X 5.CUHK

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We have now simulated a variety of targets for both Warm Dense Matter (WDM) and Heavy Ion Fusion (HIF)

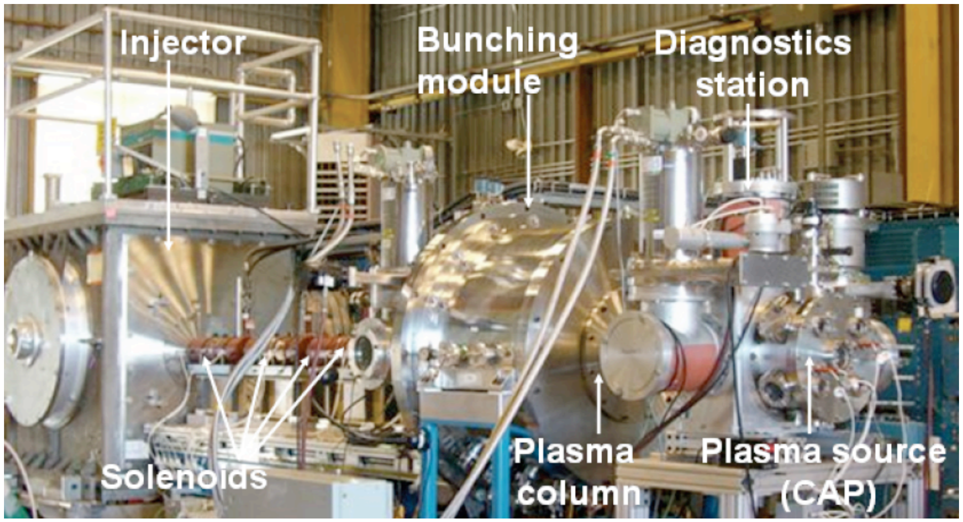
1. NDCX I simulations for WDM
   a. planar targets

2. NDCX II simulations for WDM
   a. planar target simulations
   b. metallic foams composed of alternating solid layers and voids
   c. cylindrical "bubbles"
   d. spherical bubbles

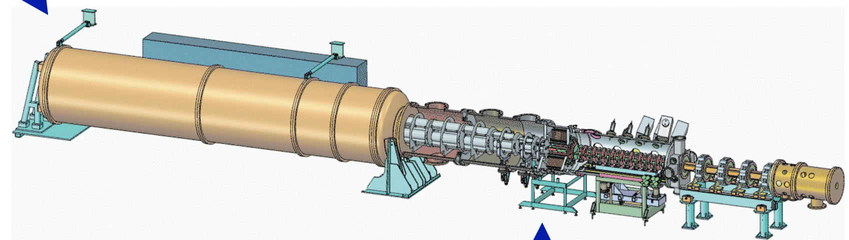
3. Direct drive simulations for HIF

4. NDCX II simulations (in support of direct drive HIF)
   a. DISH simulations: two-pulse and ramped pulse
   b. Hydra simulations: two pulse

The HIFS VNL has developed a plan for using present and future accelerators for WDM and HIF experiments



Today:



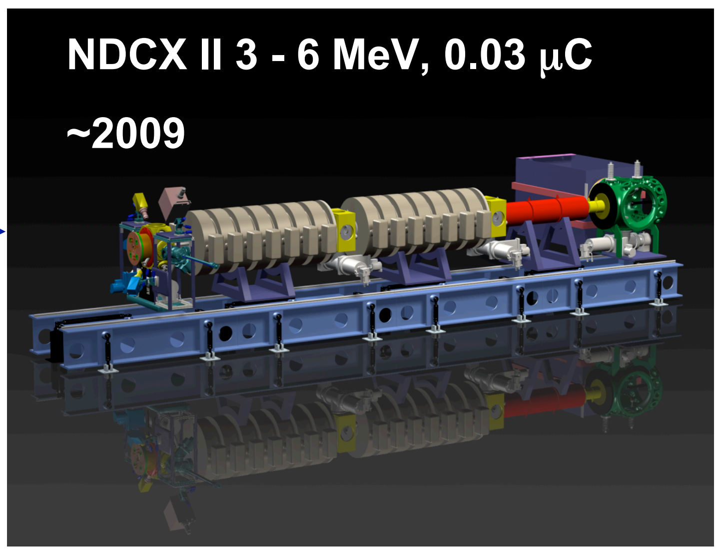
HCX

1.7 MeV, ~0.025 μC

NDCX I

0.35 MeV, 0.003 μC

Soon



Future

IB-HEDPX (with CD0)
5 - 15 year goal
20 - 40 MeV, 0.3 - 1.0 μC
WDM User facility

HIDDIX
10 - 20 year goal
~ 1 GeV, a few kJ Machine
HIF target implosion physics

HIFTF
20 yrs
~1.5 MJ

The VNL uses three hydrodynamics codes for target simulations

DPC: 1D

- EOS based on tabulated energy levels, Saha equation, melt point, latent heat
- Tailored to Warm Dense Matter regime
- Maxwell construction
- Ref: R. More, H. Yoneda and H. Morikami, JQSRT 99, 409 (2006).

DISH: 1D (cartesian), perfect gas or Van der Waals EOS

- Ref: R. More, DISH User Manual

DISHr: 1D (adapted to spherical coordinates (r,t)) by Siu Fai Ng)

HYDRA: 1, 2, or 3D

- EOS based on:
  - QEOS: Thomas-Fermi average atom e-, Cowan model ions and Non-maxwell construction
  - LEOS: numerical tables from SESAME
  - Maxwell or non-maxwell construction options
  - Ref: M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, POP, 8 2275 (2001)

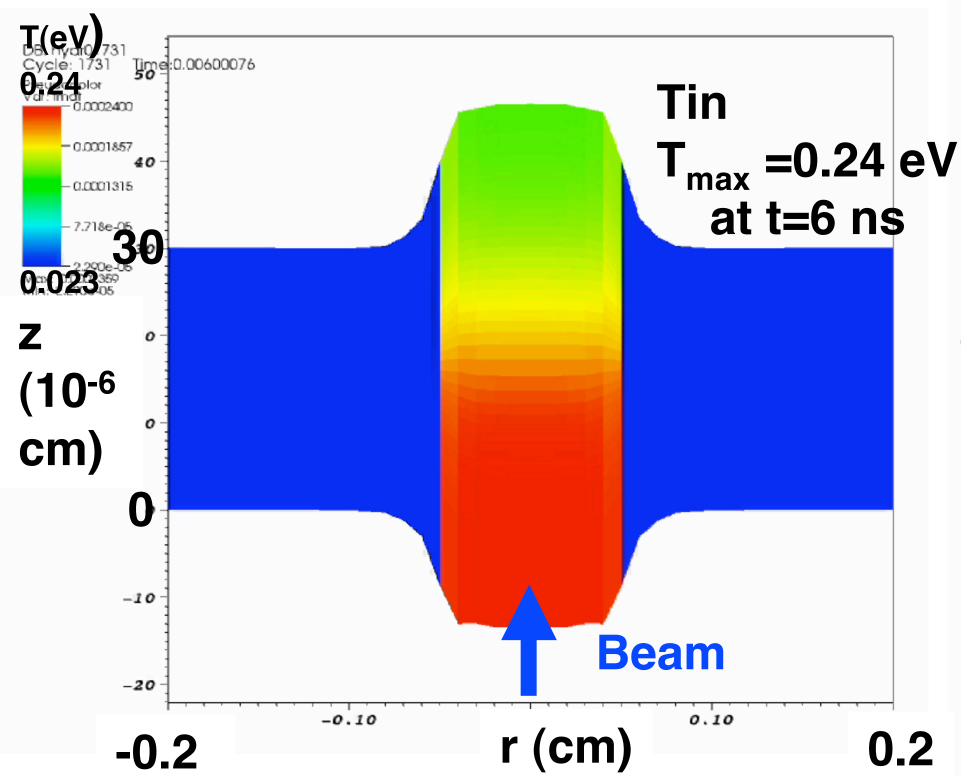
NDCX I planar targets are predicted to reach temperatures of a few tenths of an eV for two-phase studies

Simulation assumptions:

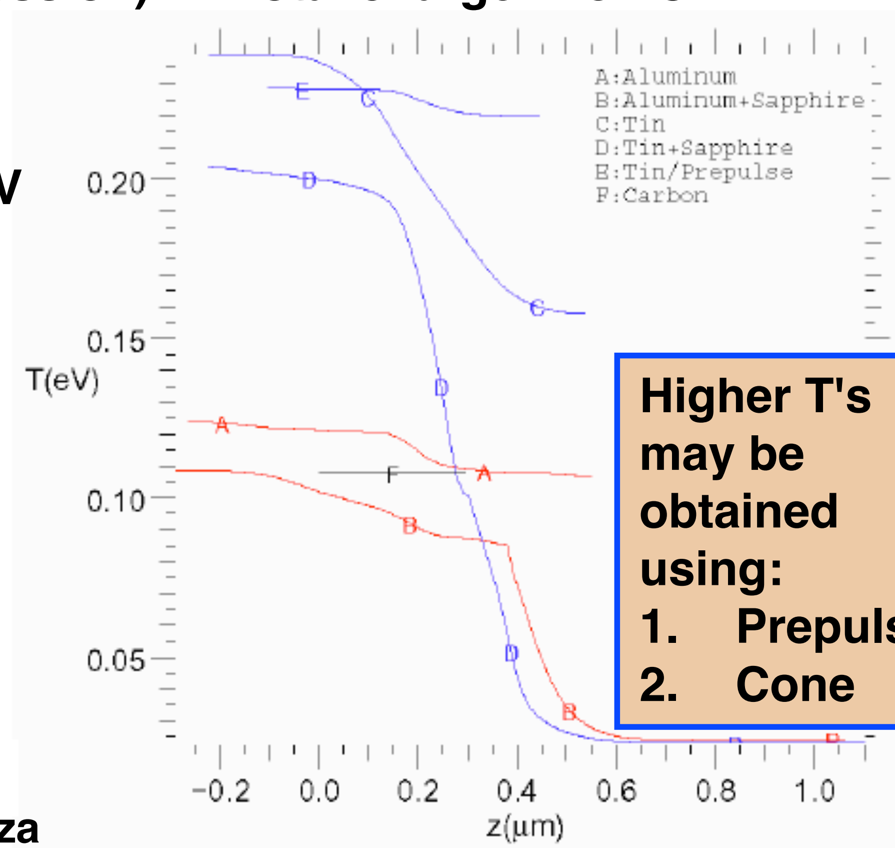
Ion energy: 350 keV   Energy fluence: 0.1 J/cm^2 Spot radius: 0.5 mm

Pulse duration: 2ns FWHM   Total energy deposited: 0.8 mJ

Peak current: 1 A (40 times compression)   Total charge: 2.3 nC



HYDRA simulations by Enrique Henestroza (see HIF08 poster)



Higher T's may be obtained using:

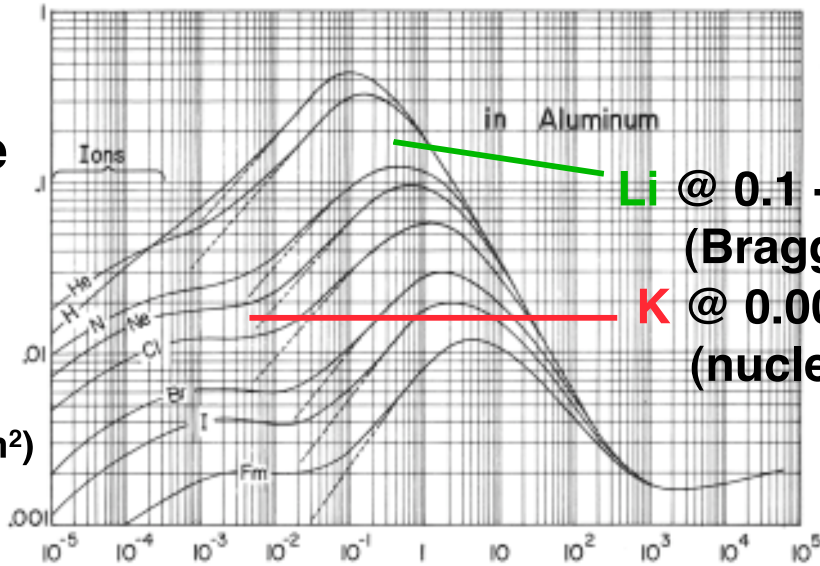
1. **Prepulse**
2. **Cone**

NDCX II will operate at the Bragg peak using Lithium ions

Energy loss rate

$$-\frac{1}{Z^2}\frac{dE}{dX}$$

(MeV/mg cm²)

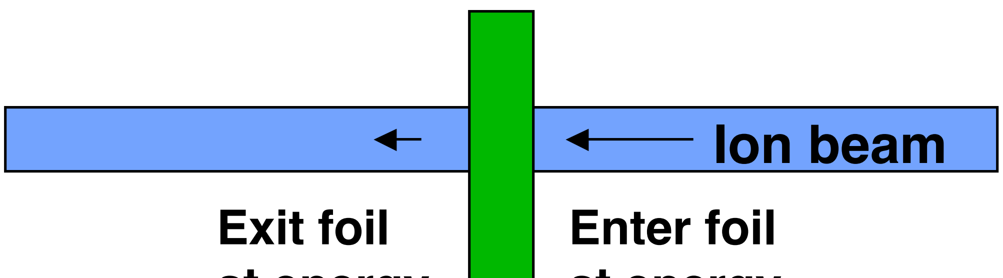


Energy/Ion mass (MeV/amu)

Li @ 0.1 - 0.4 MeV/amu = NDCX II (planned)
(Bragg peak)

K @ 0.003 - 0.009 MeV/amu = NDCX I
(nuclear stopping plateau)

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

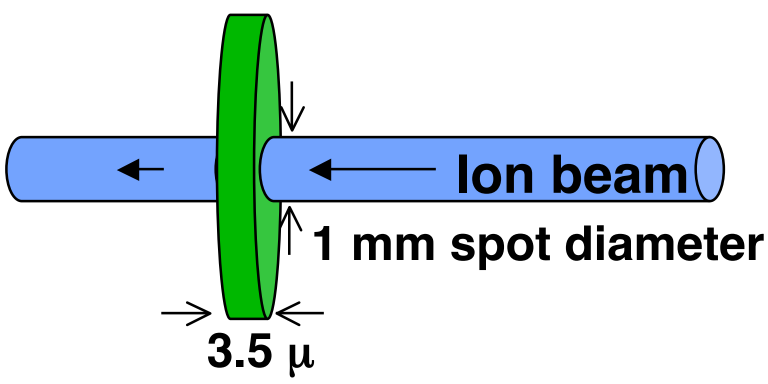


Exit foil at energy ~0.5 x E_{peak}

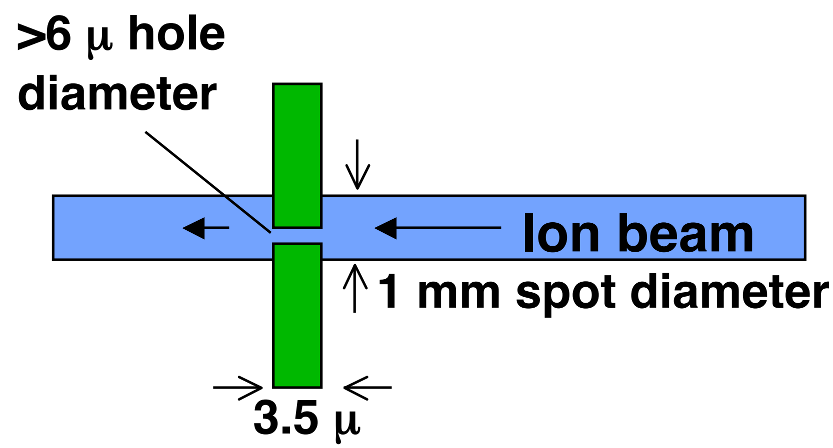
Enter foil at energy ~1.5 x E_{peak}

uniformity and fractional energy loss can be high if operate at Bragg peak (Larry Grisham, PPPL)

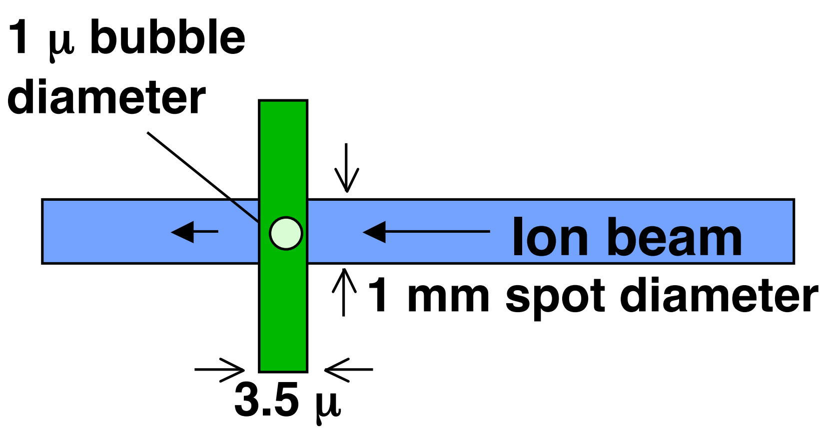
Several target options have been considered for WDM studies on NDCX II



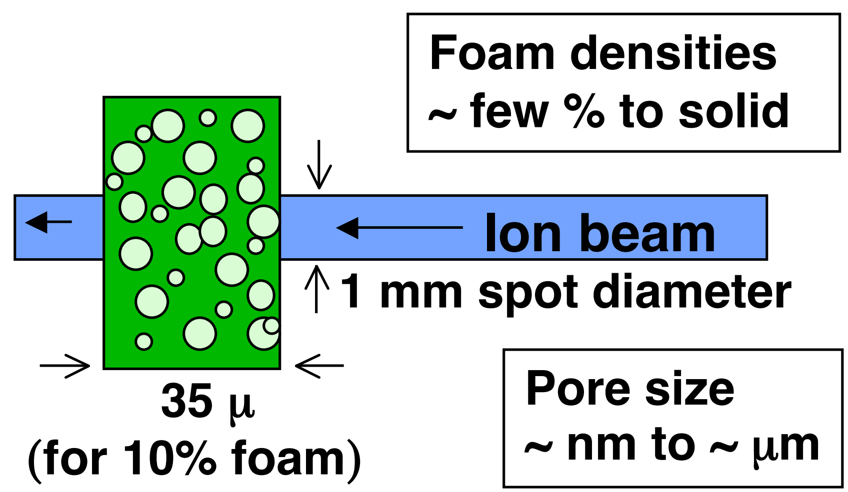
Solid planar targets



Cylindrical "bubble" targets



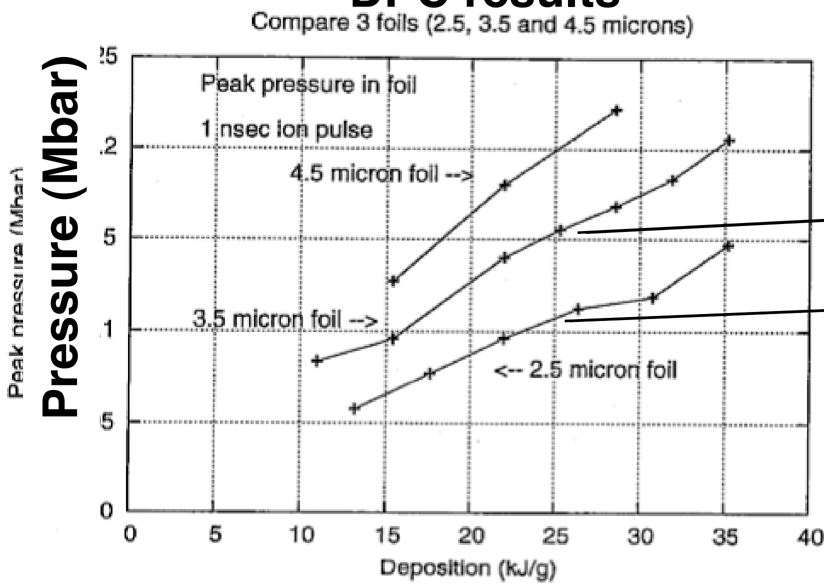
Spherical bubble targets



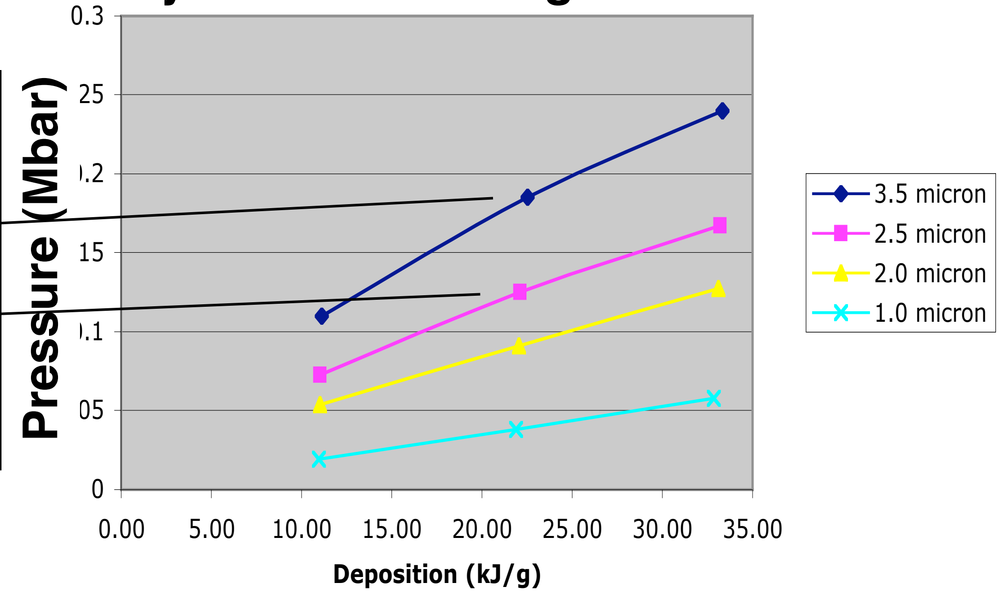
Foam planar targets

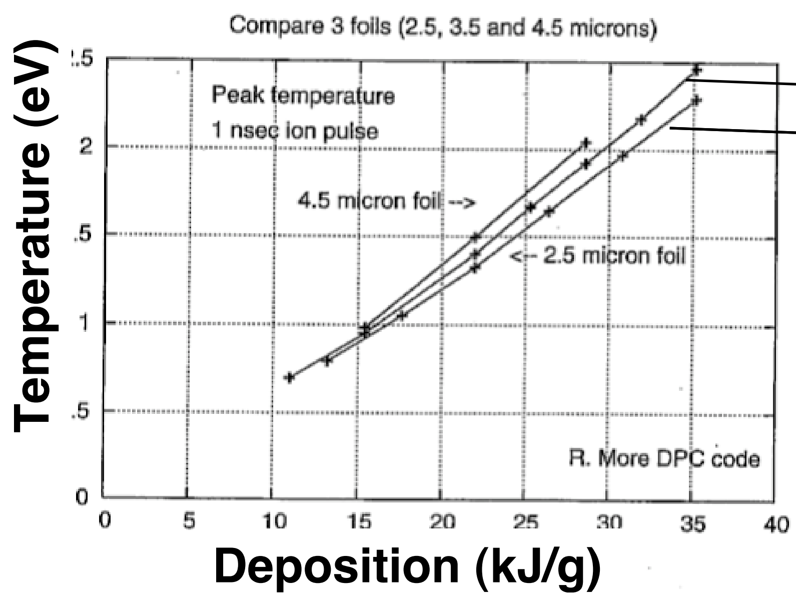
At nominal NDCXII 20kJ/g, simulations show pressures of 0.1 to 0.2 Mbar, temperatures 1.2 - 1.4 eV in solid Al

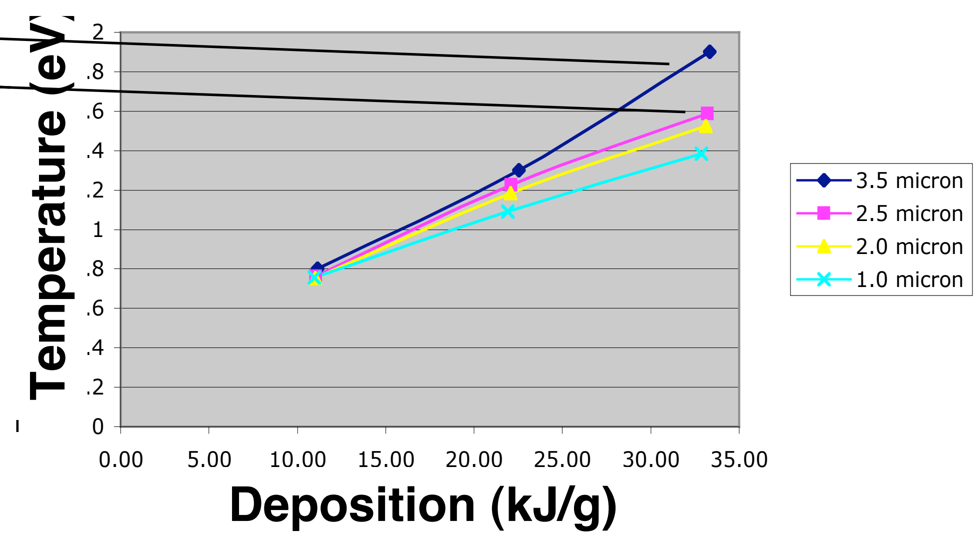
DPC results



Hydra results using QEOS

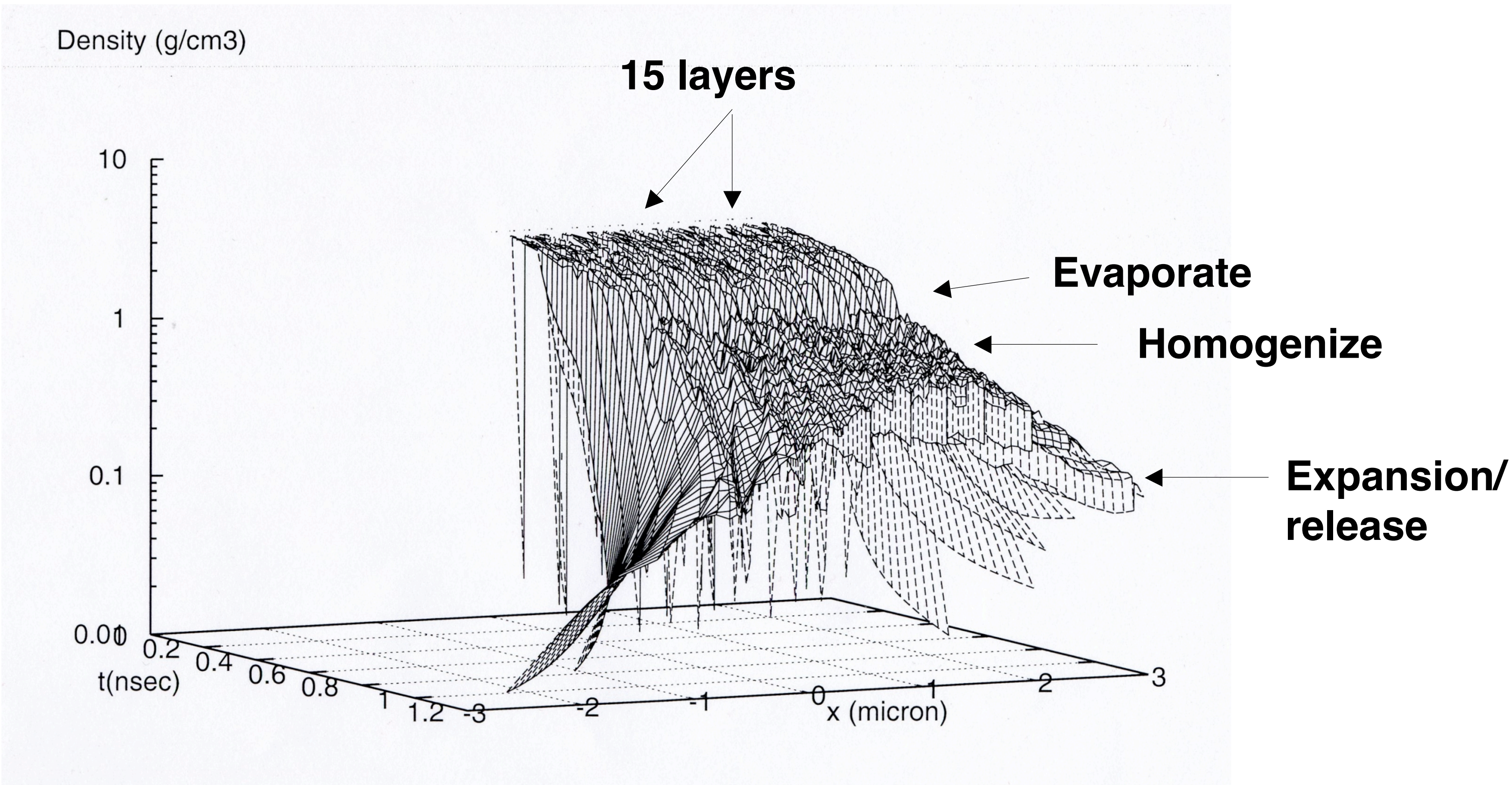






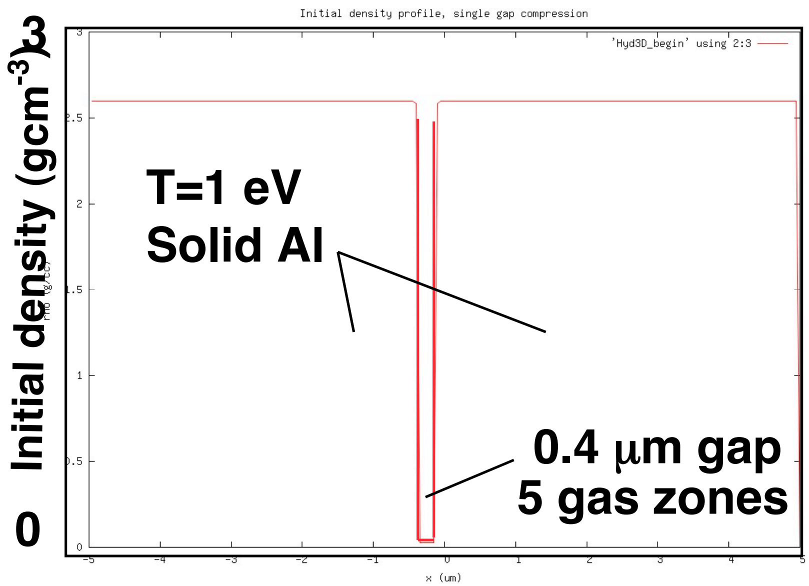
Foams have been modeled as layers of solid separated by layers of void

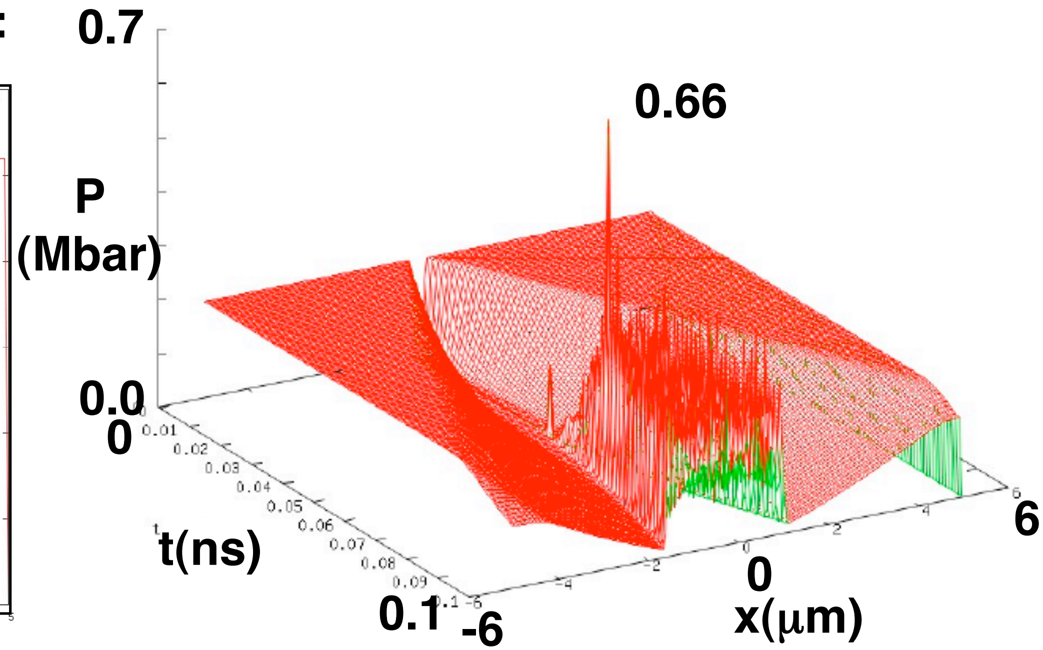
Codes used on foam modeling include: DPC (Saha based EOS), HYDRA (using QEOS), and DISH (using van der Waals EOS)

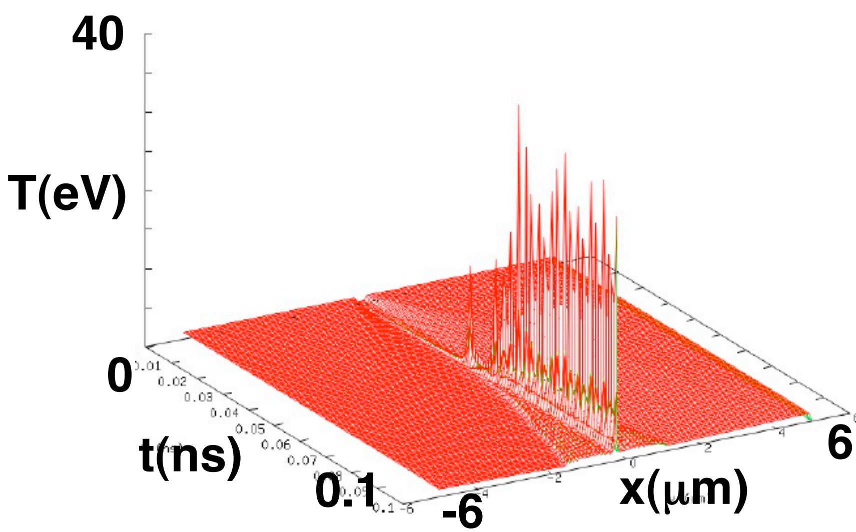


R. More observed in early layered foam simulations that when layers collided, higher temperatures were reached

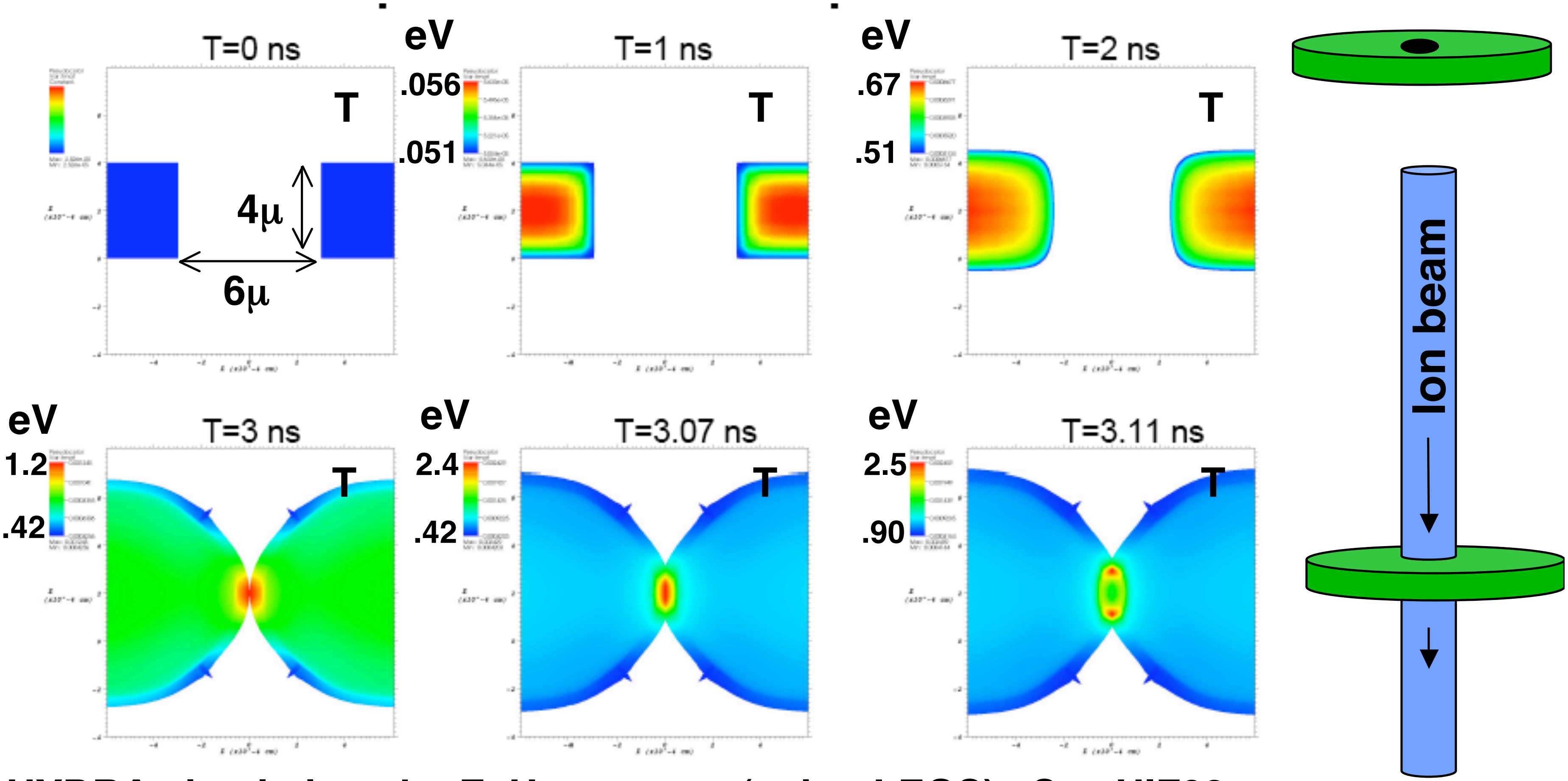
DISH simulation (by A. Zylstra):







If instead of colliding slabs, a cylindrical hole is placed in foil, convergence increases pressure



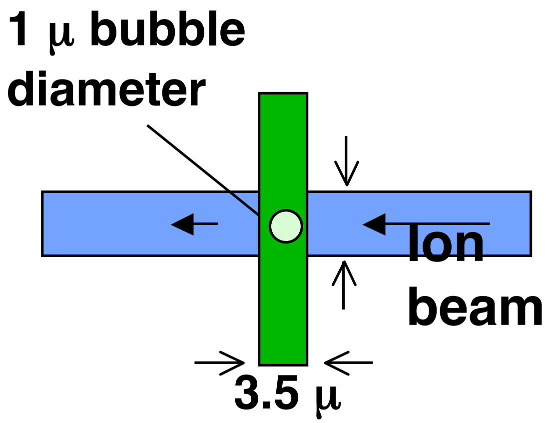
HYDRA simulations by E. Henestroza (using LEOS). See HIF08 poster.

Solid Tin target. 2.8 MeV Li^+, 10 J/cm^2 assumed.

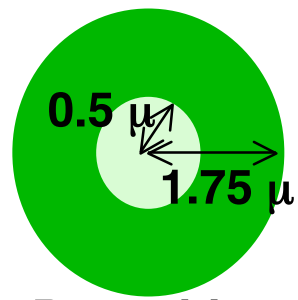
T_{max} = 2.6 eV; P_{max} = 1.3 Mbar ρ_{max}= 11 g/cm^3 (ρ_{init}= 7 g/cm^3); v_{imp} = 3.5 km/s

Advantage: relatively easy to manufacture and diagnose

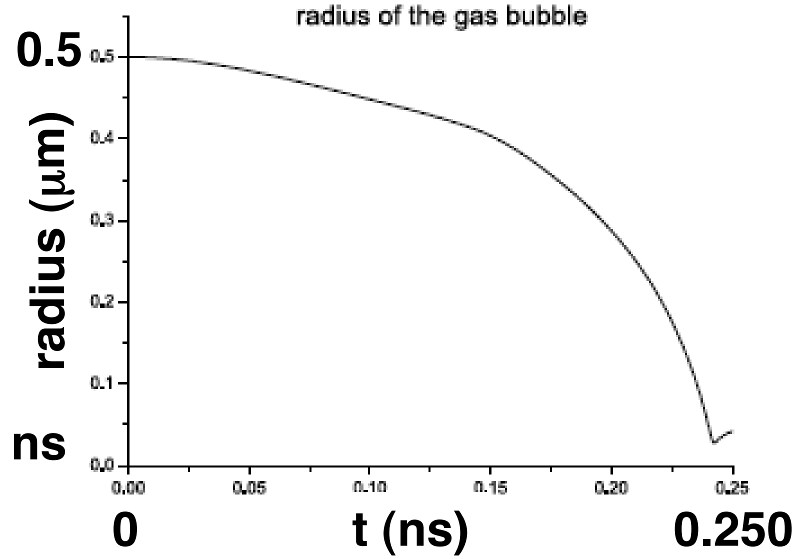
If instead of a cylindrical hole, a spherical void is placed in the foil, higher pressures are possible



Simulation:

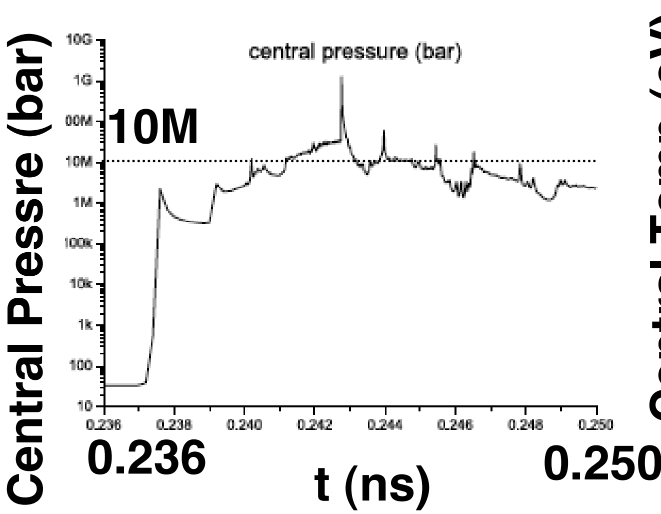


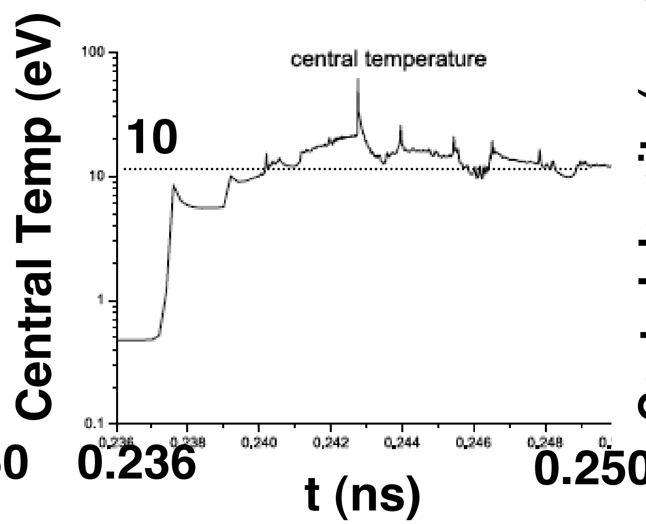
Deposition:
25 kJ/g/ns for 1 ns

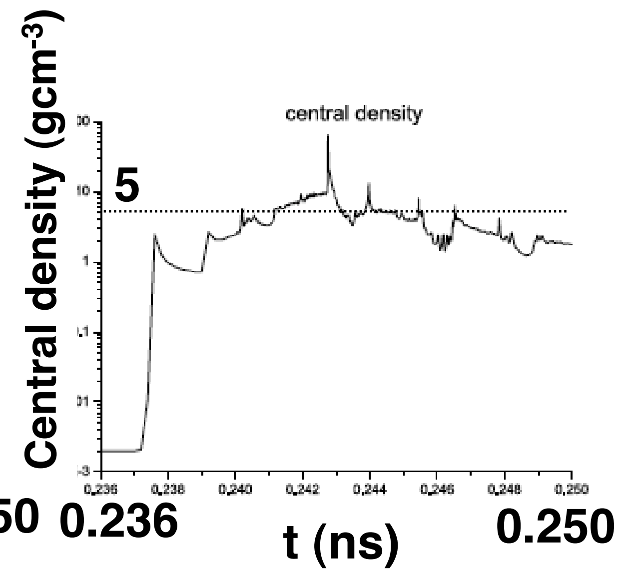


Simulations by Siu-Fai Ng
(using DISHr, QEOS) see HIF08 poster

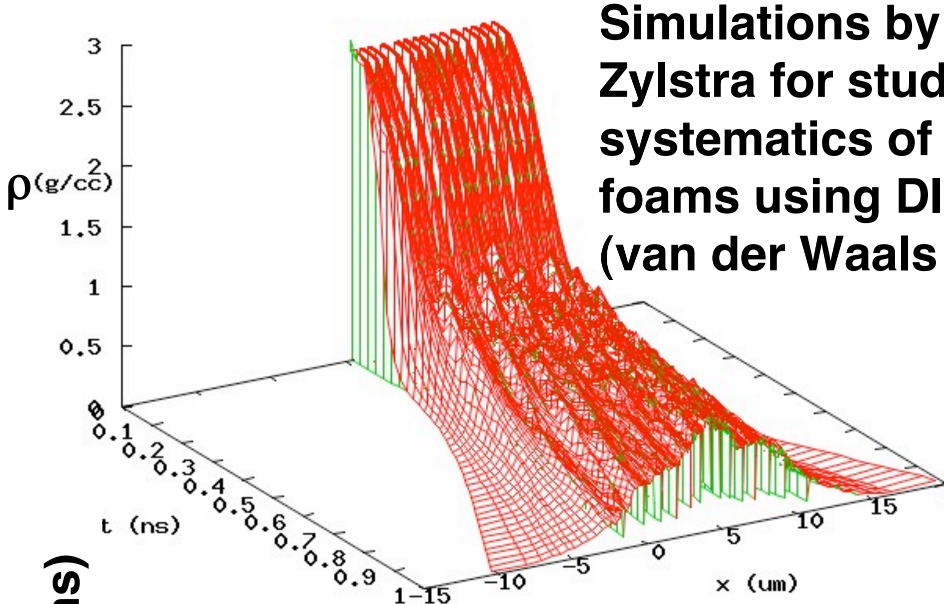
$P_{max} > 10$ Mbar, $T_{max} > 10$ eV, $\rho_{max} > 5$ g/cm^3



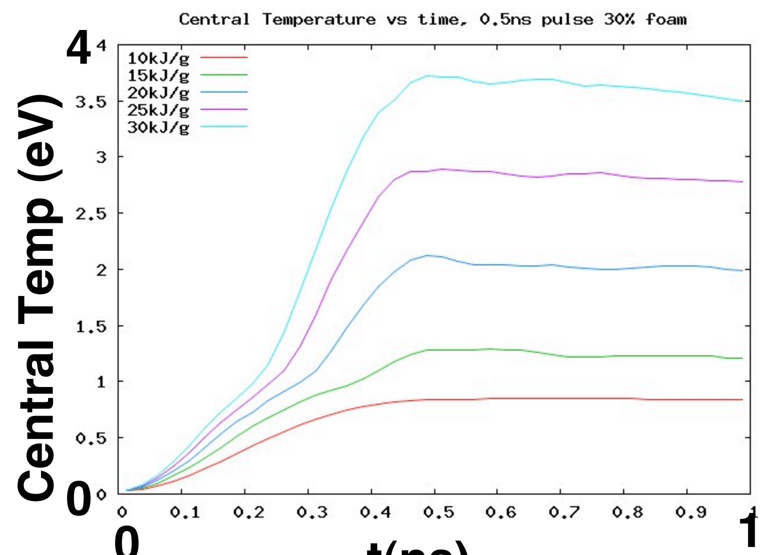


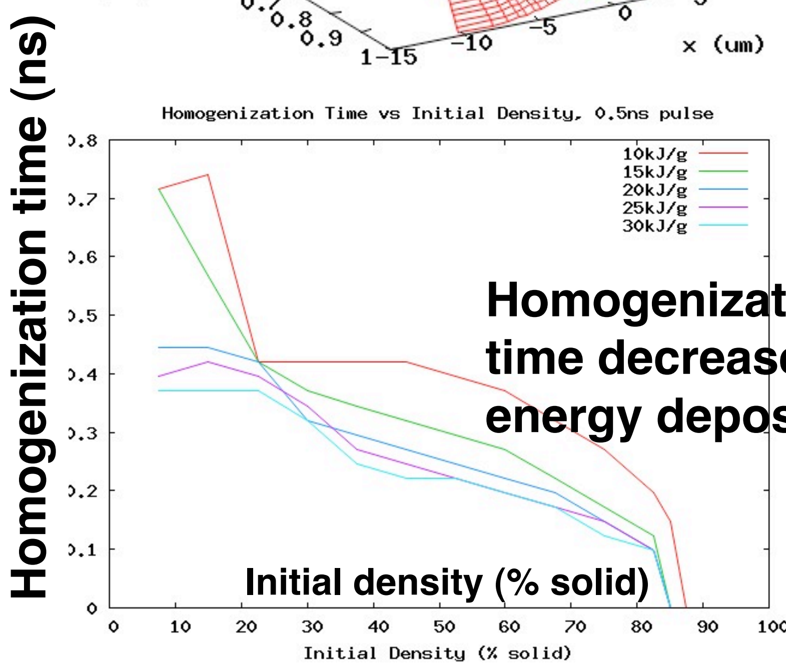


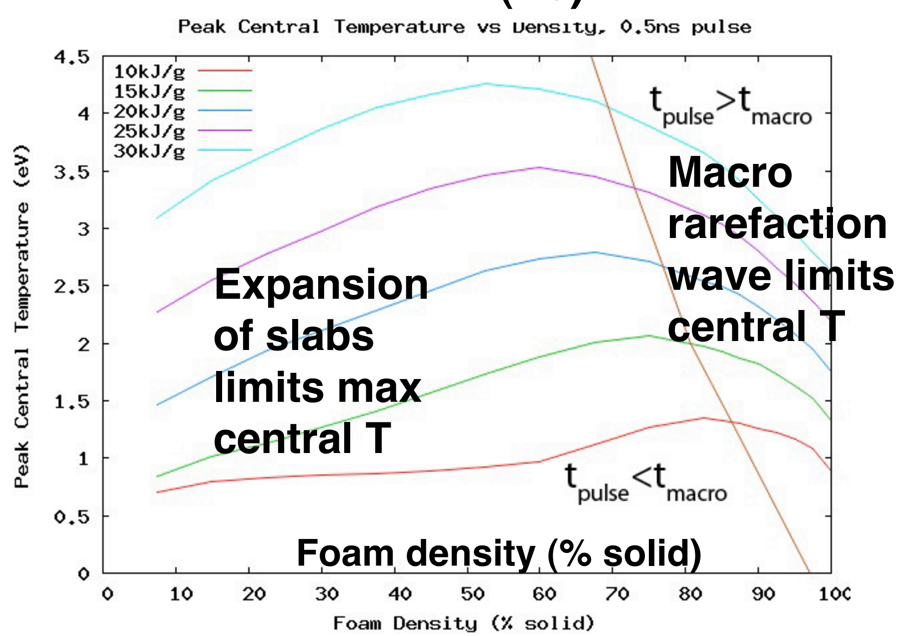
"Planar" foams have been used to model homogenization, velocity, and temperature evolution



Simulations by Alex Zylstra for study of systematics of planar foams using DISH (van der Waals EOS)

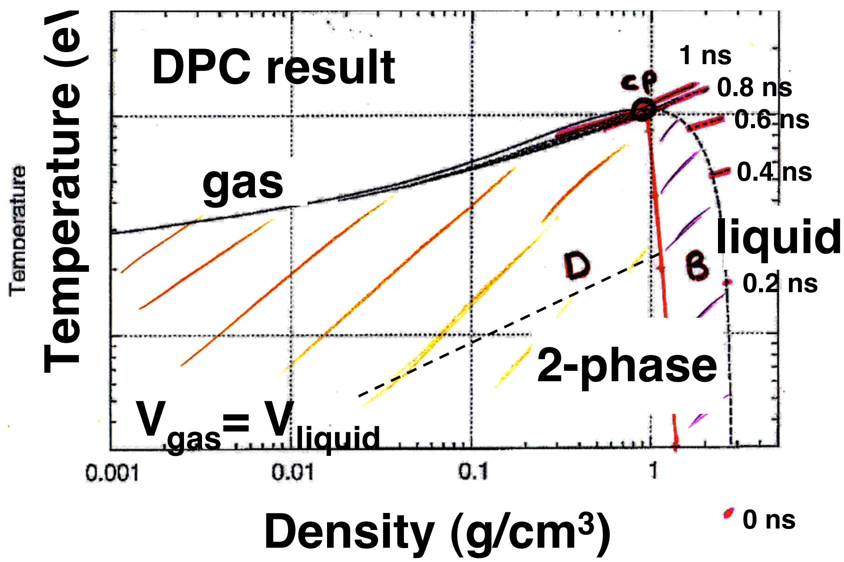


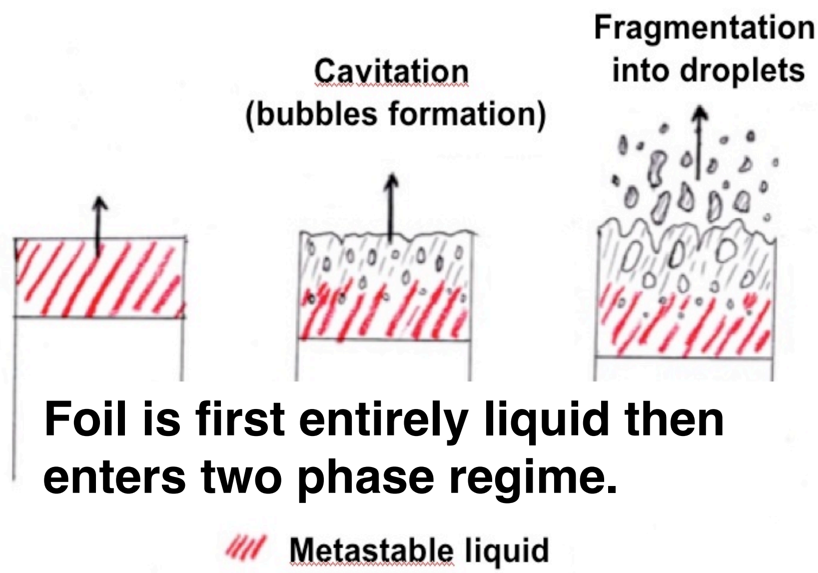




Formation of droplets during expansion of foil is being investigated using a kinetic code

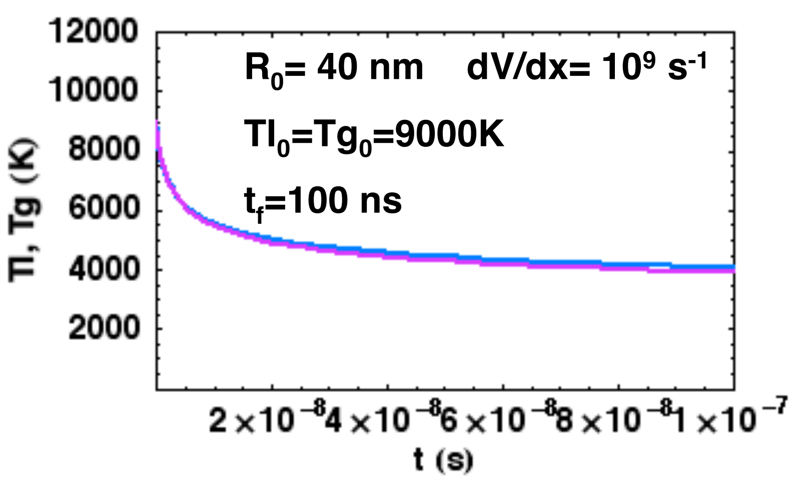
Example of evolution of foil in ρ and T

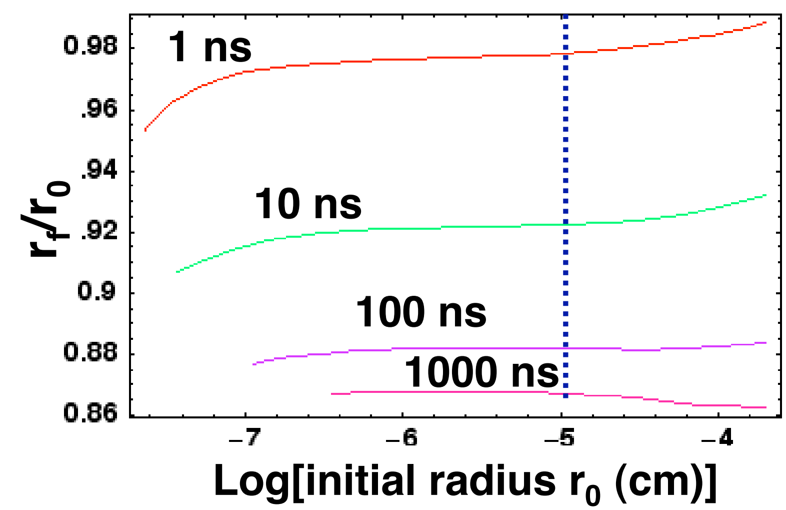




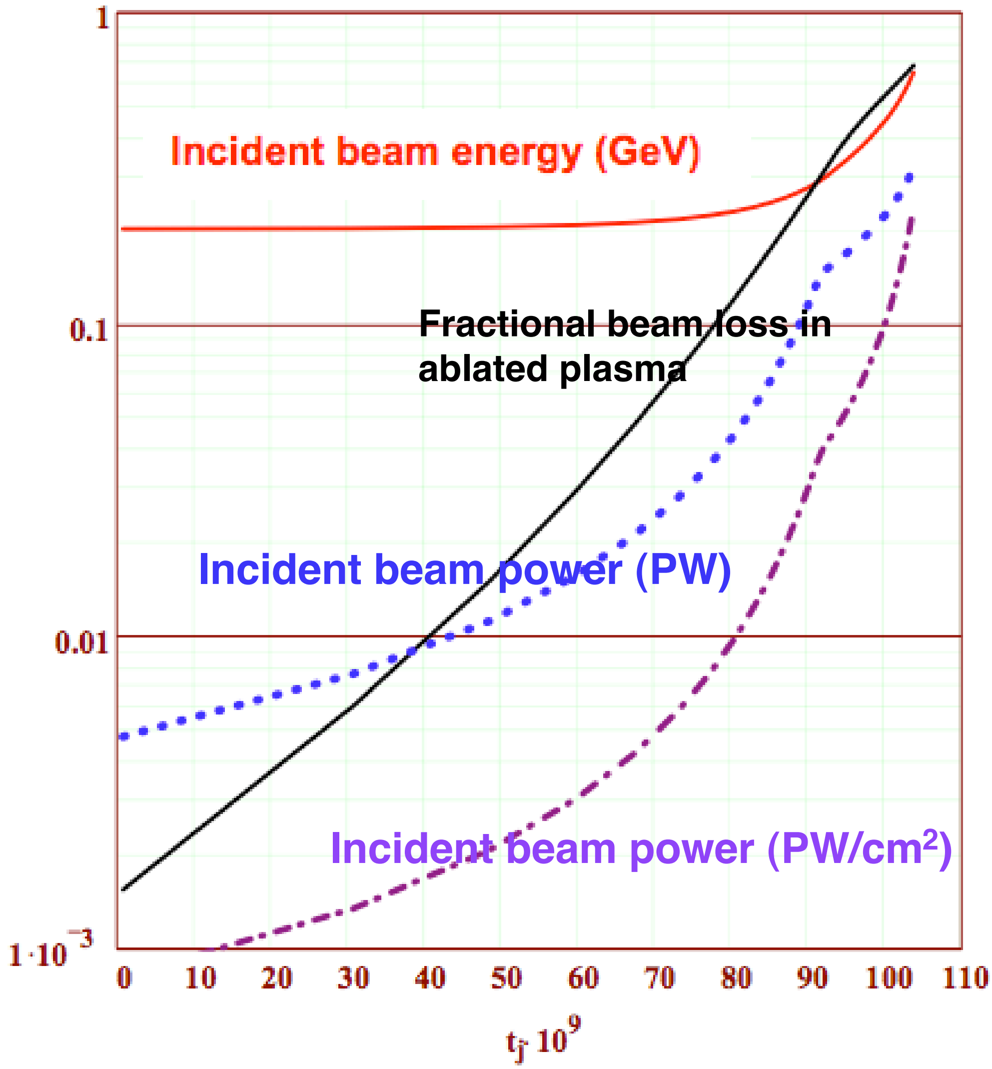
Foil is first entirely liquid then enters two phase regime.

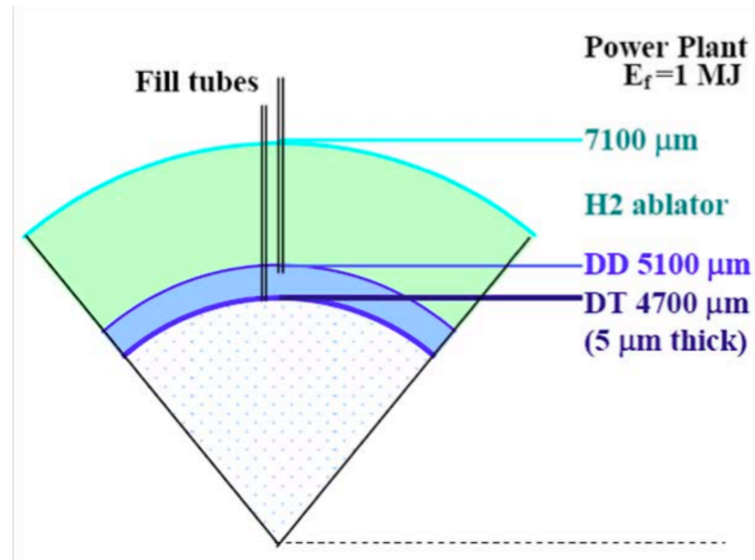
(Ref: J. Armijo, master's internship report, ENS, Paris, 2006; Armijo et al APS DDP 2006, and in prep.)





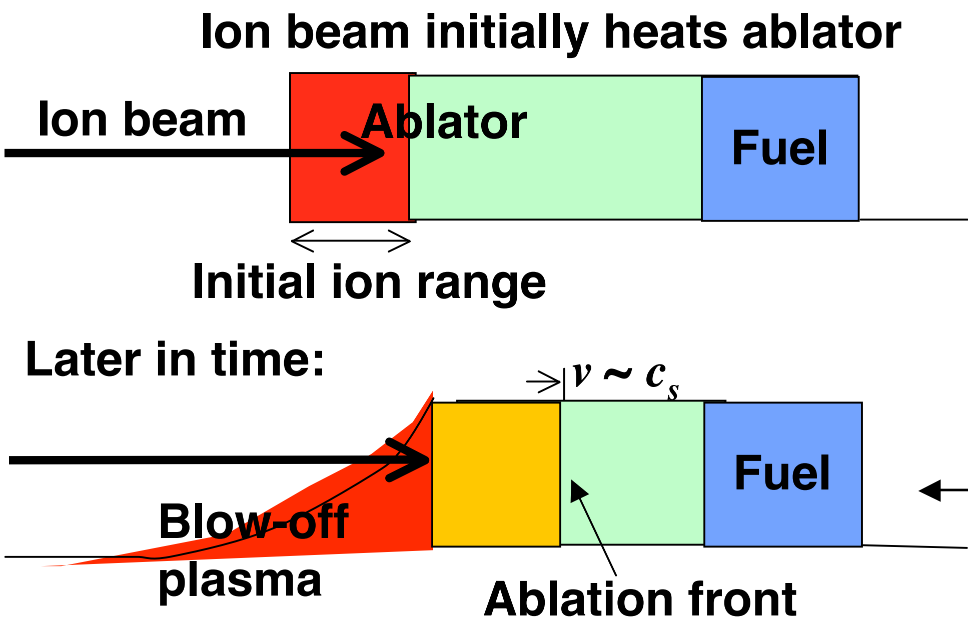
We are investigating ion direct drive for its efficient capsule coupling and reduced driver size

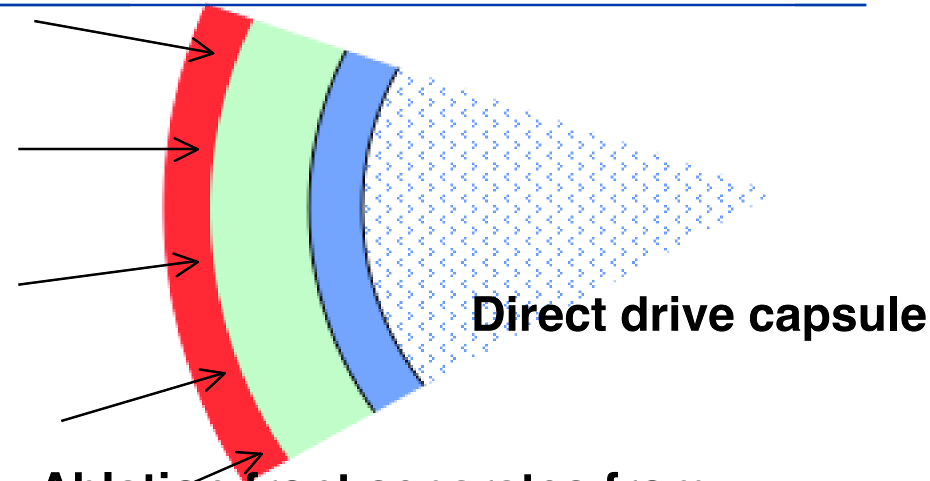




From B.G. Logan, "Exploring a unique vision for HIF," Jan 2008.

Problem: with direct drive, outflowing plasma causes ions to deposit energy at increasing distance from ablation front





Ablation front separates from location where energy is deposited

==> Low coupling efficiency

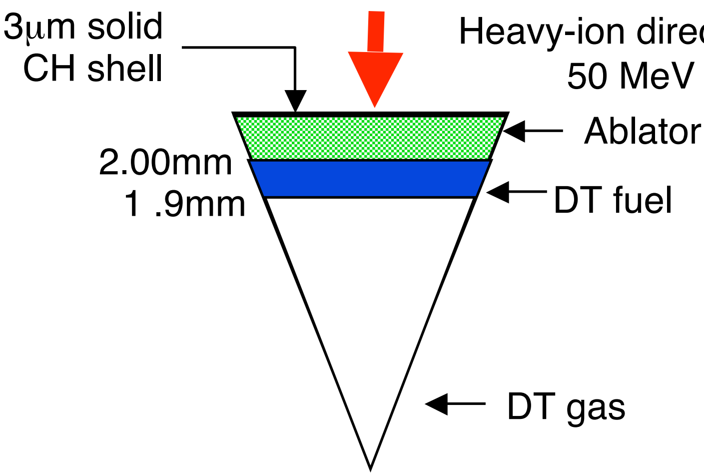
Solutions:

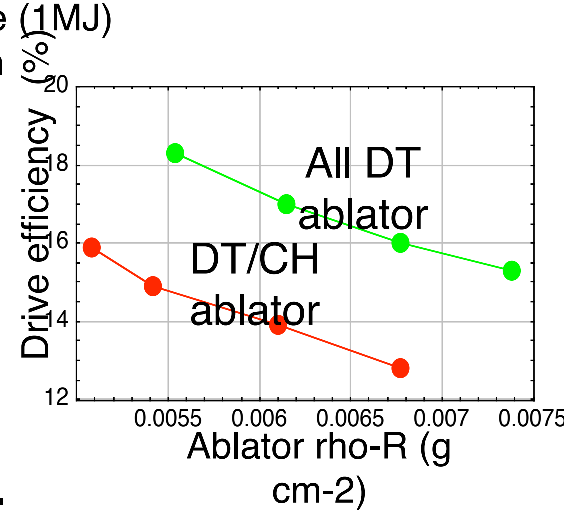
1. Passive approach: Ion beam heating causes electron thermal speed to go above ion velocity ==> range lengthens, and ion beam can stay close to ablation front, (if ion energy is sufficiently low)

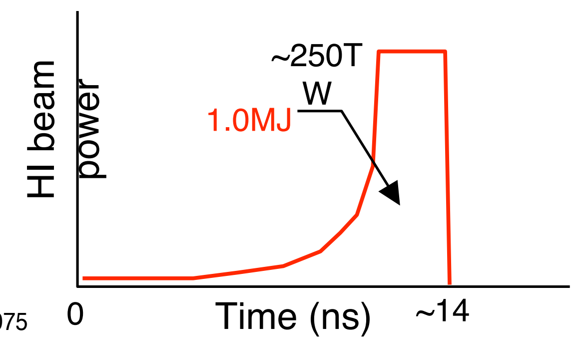
2. Active approach: Ramping ion beam energy over the course of the pulse, will also increase range. But range, couples to hydro, which couples to range.

Heavy-ion direct drive LASNEX runs by John Perkins found gains ≥ 50 at 1MJ with high coupling efficiency (15%).

Coupling efficiency ≡ fuel shell kinetic energy/ion beam energy





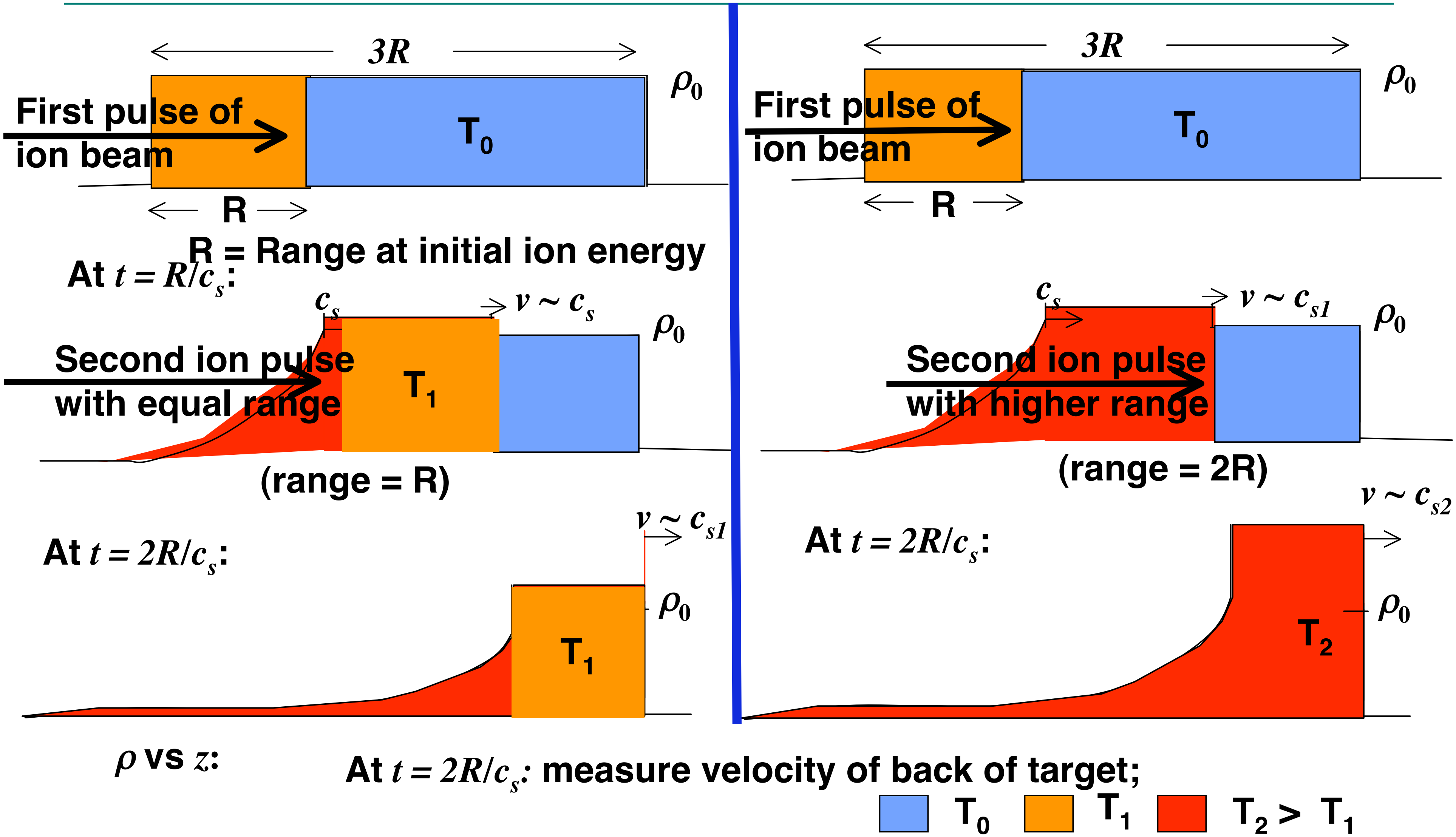


(See Logan, Perkins, Barnard, Phys. of Plasmas, 2008, in press).

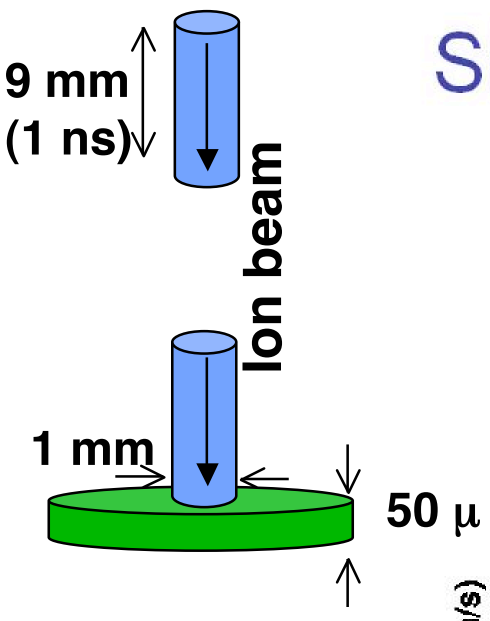
Higher efficiencies and gains may be possible by using energy ramp

	Coupling efficiency	Target gain (at 1MJ drive)
Laser Indirect Drive	~ 2-4%	~ 10
Laser Direct Drive	~ 5-8%	~ 25
Heavy ion direct drive with energy ramp	~ 25%	~ 100

A double-pulse experiment on NDCX II can demonstrate an improvement in coupling efficiency with increasing ion range experimentally

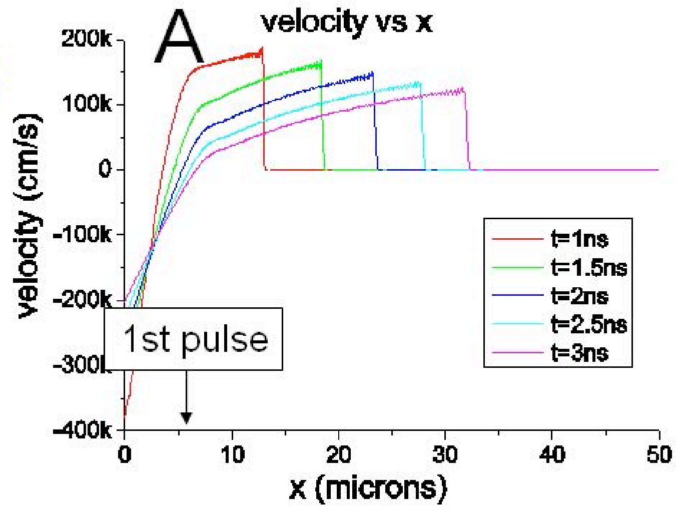


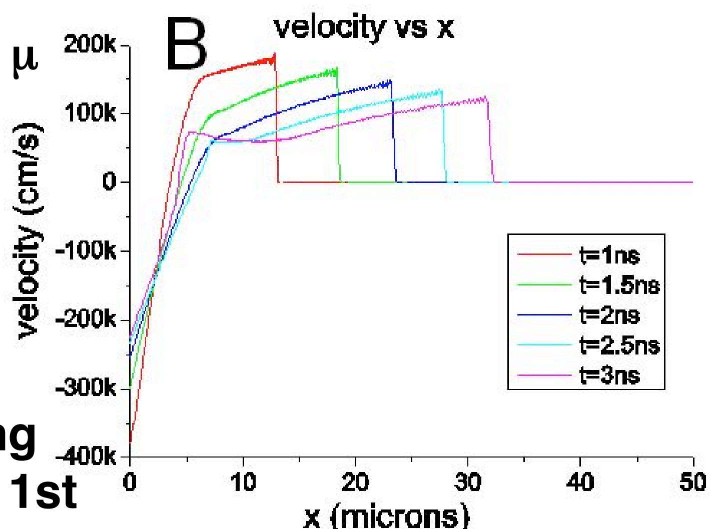
Simulations using DISH (using van der waals) confirm benefits of double pulsing

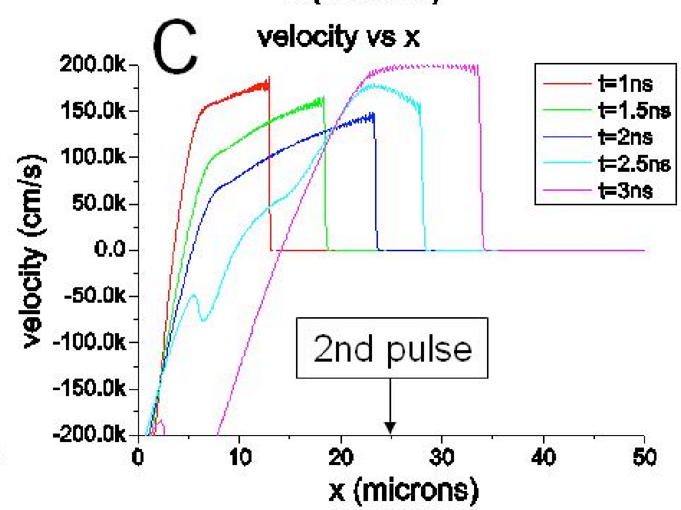


Simulation Results

Case	E_1	E_2
A	1 MeV	0 MeV
B	1 MeV	1 MeV
C	1 MeV	6 MeV

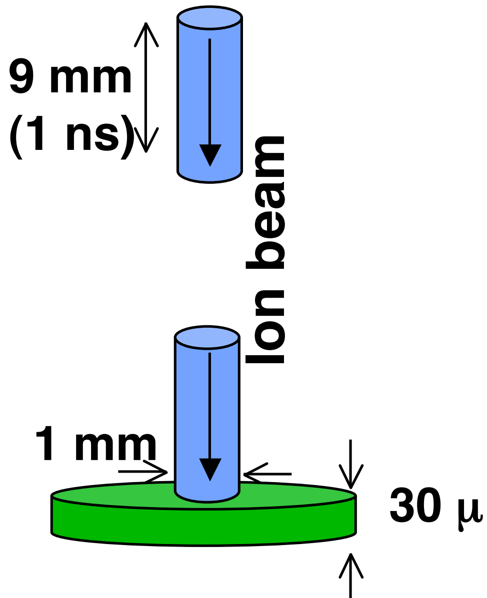




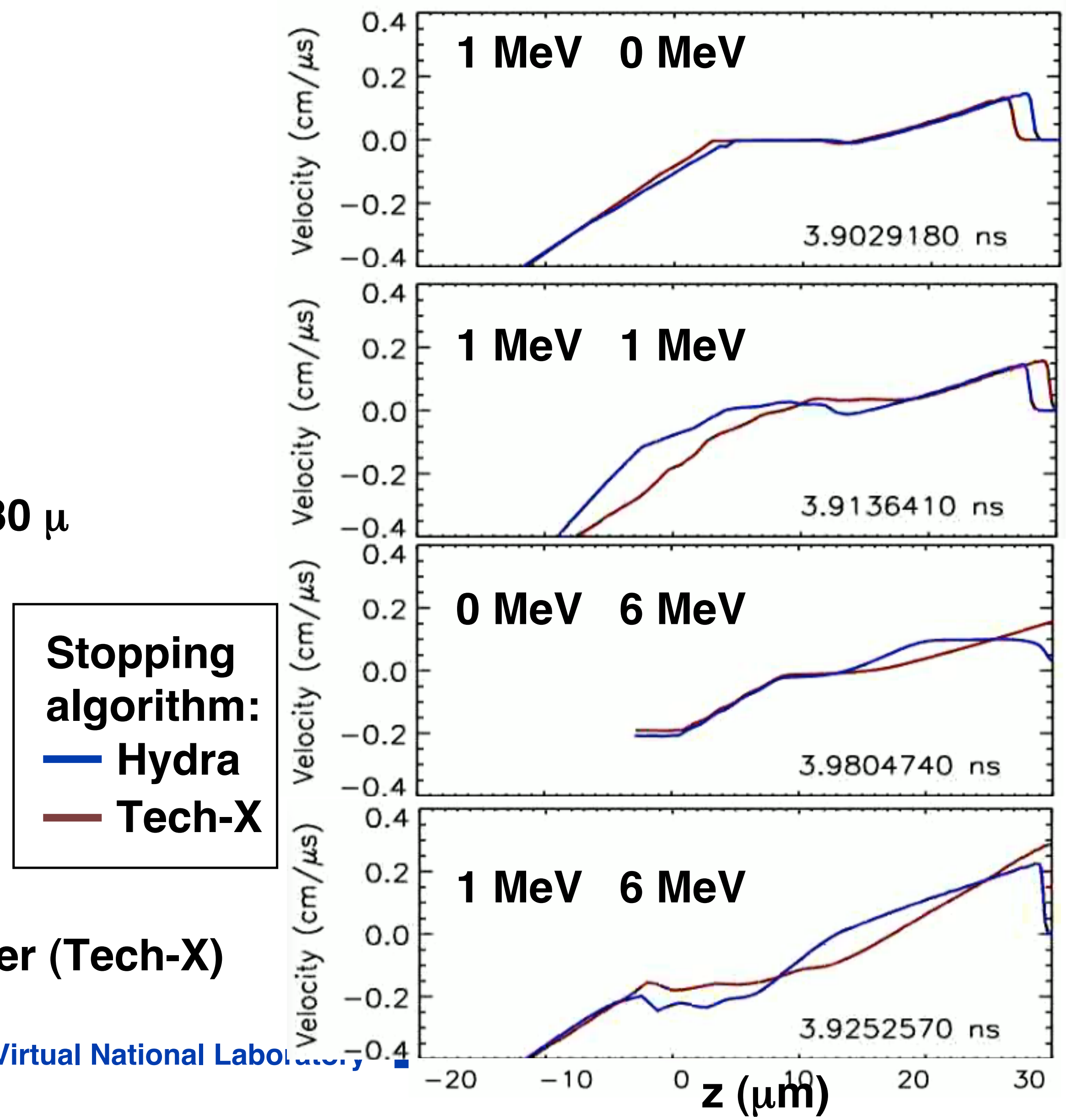


Ion: Li^+ or Li^{++}
Target: Solid Ar
Intensity: 30 J/cm2 (each pulse)
Each pulse: 1 ns long
2nd pulse, 1ns after 1st
Simulations by Siu Fai Ng (see poster HIF08)

Double pulse simulations using HYDRA in metallic Al foam show that alternative room temp experiment possible



Ion: Li^{+} or Li^{++}
Target: 50% Al foam
Intensity: 30 J/cm2
(each pulse)
Each pulse: 1 ns long
2nd pulse, 1ns after 1st
Simulations by Seth Veitzer (Tech-X)



Conclusions

We have now simulated a number of target concepts for NDCX I, NDCX II, and ion direct drive

Simulations suggest we will be able to start exploring the metallic two-phase regime in NDCX I

In NDCX II, planar targets at ~ 1 eV, .5 MBar are predicted;
cylindrical imploding bubbles will reach a few eV, 1 MBar
spherical imploding bubbles can reach ~10 eV, 10 MBar
Foam homogenization, expansion, and peak temperature being modeled using "planar" foams. Droplet formation being studied using kinetic model.

For HIF, we are exploring direct drive concepts that have high coupling efficiency, by utilizing temperature dependent range and ramped ion energy

NDCX II will be able to test key aspect of direct drive target concept: changing ion energy to keep ion deposition point close to ablation front